Circumstellar Emission and Absorption from Post-AGB Stars.

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ABSTRACT

We present the results of multi-wavelength observations, involving IUE, ground-based observations, and ISO, to study the circumstellar environment of two binary post-AGB stars, HR 4049 and HD 213985, at different orbital phases. These objects offer a unique opportunity to probe the nature of dust in absorption as well as in emission. Some conclusions can be drawn concerning the carriers of the 220nm bump and the far-UV extinction rise. Progress for this research has heavily relied on the flexibility of IUE to carry out regular observations in a crucial wavelength range.

Key words: circumstellar extinction, post-AGB stars

1. INTRODUCTION

The IUE satellite has been instrumental in describing the interstellar extinction law, in terms of a component which is linear in the inverse wavelength, the 220nm bump, and a far-UV rise. The identification of the carriers of the different extinction features is still a matter of debate, to a large extent because it is rare that correlations can be found between dust absorption and emission: the interstellar clouds that absorb the UV are rarely seen in the IR, and circumstellar dust around evolved stars is optically thick to UV radiation.

The circumstellar material around optically bright post-AGB stars provides us with a remarkable opportunity to study both the extinction and emission from dust. Indeed, the dust ejected at the end of the AGB evolution still produces an observable infrared excess for such stars, and in favourable cases - i.e. when the expanding envelope has become transparent to a certain extent, and the increasing effective temperature of the central star has led to a substantial UV and optical flux - the extinction properties of this dust can also be studied. Moreover, since the circumstellar matter originates from a previous evolutionary phase of high stellar mass loss, the composition of the circumstellar material is expected to be more chemically homogeneous than in the interstellar medium. Finally, the circumstellar environment imposes specific constraints on the physical and chemical circumstances for dust formation and processing.

In this contribution, we discuss multi-wavelength observations of the circumstellar environment of two post-AGB objects, HR 4049 and HD 213985. For both objects, the circumstellar extinction appears to be cyclically variable; this cyclicity has been detected from optical data, and subsequently IUE has been used in order to describe the variability of the UV extinction. For both objects we confront the extinction results with the IR emission as it was observed with the SWS spectrograph on board of the Infrared Space Observatory (ISO).

2. PROGRAMME STARS

HR 4049 and HD 213985 are relatively bright early-type supergiants (table 1) whose spectral energy distributions reveal the presence of warm cirumstellar dust shells (Lamers et al. 1986; Waelkens et al., 1987). The high luminosity, kinematics, presence of circumstellar dust, and high galactic latitude are best explained in terms of a late evolutionary stage of low-mass stars, more specifically the short phase between the asymptotic giant branch (AGB) and the planetary-nebula phase. These objects are not typical post-AGB stars, however, since both prove to be single-lined spectroscopic binaries with orbital periods of 430 and 260 days, respectively (Waelkens et al. 1991, Van Winckel et al. 1995).

Table 1. Fundamental parameters of the two programme stars.

	HR 4049	HD 213985
α_{2000}	10 18 07.6	22 35 27.3
δ_{2000}	-28 59 31.5	-17 15 26.5
b	$+22.9^0$	-57.1^0
$< m(v) >$	5.5	8.8
T_{eff}	7500 K	8200 K
log(g)	1.0	1.5
[Fe/H]	-4.8	-1.0
$E(B-V)_{interstellar}$	0.12	0.15
Orbital Period	430 days	260 days
$\pi_{hipparcos}$	1.5 ± 0.63	not significant

The geometry of the cirumstellar material could be inferred from detailed optical photometric monitoring campaigns. Both objects display variable circumstellar extinction, phased with the orbital motion. This variability is illustrated in figure 1, where the visual magnitude, Geneva [U-B] colour and radial velocity curves of HR 4049 are shown folded on the 430 day orbital period. Light minimum, i.e. when the extinction is largest, is reached at inferior conjunction, while the extinction is minimal and close to vanishing at superior conjunction. This photometric behaviour can best be explained by variable obscuration during orbital motion by a circumbinary dust ring. The amount of reddening changes during orbital motion within a slightly inclined disc (Waelkens et al., 1991). A similar photometric behaviour is observed for HD 213985. The cycle-to-cycle variations that are observed in the photometric curves of both stars indicate that the circumstellar environment is somewhat patchy; nevertheless, despite the erratic component in the extinction changes, the orbital period is recovered as the most significant period in the brightness variations of both stars.

With [Fe/H] = −4.8, HR 4049 is the proto-type of the extremely iron-deficient post-AGB binaries, which owe their extreme photospheric abundance pattern to accretion of circumstellar gas devoid of refractory elements (Bond 1991; Van Winckel et al. 1992). The photospheric chemical patterns of HD 213985 are less extreme but are also influenced by this depletion process (Waelkens et al., 1998). It could well be that the geometry and stability of a circumbinary disc may be crucial to make the chemical depletion process so efficient (Waters et al. 1992). The photospheric metallicity and C/O ratio is thus determined by this accretion process and not by internal mixing. this is an unfortunate circumstance for the study of the circumstellar extinction, since the photospheric abundance patterns can not be used to infer the composition of the circumstellar material.

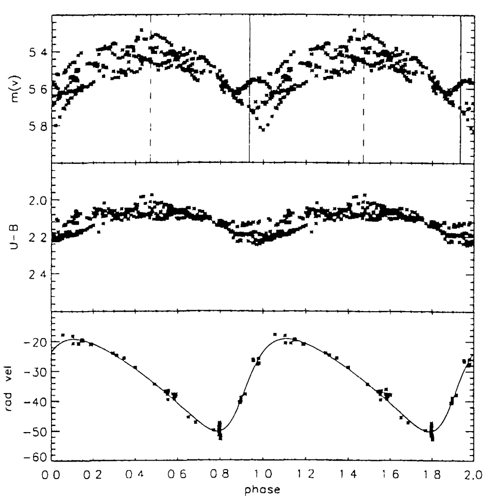

Figure 1. The visual light curve, U-B colour curve and radial velocity curve of HR 4049 folded on the 430 day binary period. The full (dashed) curve indicates the phase of inferior (superior) conjunction.

The post-third-dredge-up character of these supergiants is, however, strengthened by the carbon-rich nature of the circumstellar envelope: HR 4049 displays the UIR features in the mid-IR (usually attributed to vibrational decay of PAH molecules) that are associated with carbon-rich material, while HD 213985 displays optical circumstellar CH^+ lines (Waelkens et al. 1995). Unpublished ground-based IR measurements suggest that HD 213985 has a broad rather featureless IR excess, which could indicate that the carbon grains are in amorphous form.

3. EXTINCTION CURVE

Although both objects are in a similar evolutionary stage and display evidence for a comparable chemical history and circumstellar geometry, the UV extinction curves are drastically different. We obtained these curves using low-resolution IUE spectra at different orbital phases. Optical photometric data of stars close to the lines of sight to both objects were used to estimate the interstellar reddening, for which the mean Savage-Mathis law was used; by all means, the interstellar reddening towards both high-latitude objects is low (E(B-V) about 0.15), so that uncertainties in the interstellar reddening law hardly affect the results. After correction for the interstellar reddening, appropriate Kurucz model atmospheres were used to predict the stellar UV flux (Waelkens et al., 1995). Model parameters were estimated by calibrating the photometry at maximum light (minimum circumstellar extinction) together with a detailed study of high-resolution optical spectra. The curves shown in figure 2 were obtained by dividing the heavily smoothed dereddened IUE spectra by the model fluxes.

The circumstellar extinction of HR 4049 consists of a linear component and a far-UV rise. The uncertainty on the UV model flux may induce a systematic quantitative error on the extinction curve, but the two-component model must be basically correct. The absence of a circumstellar 220nm bump is striking.

The circumstellar extinction curve of HD 213985, on the other hand, does show the three components: a prominent bump peaking around 228nm, a 'linear' part, which flattens in the far-UV, and a far-UV rise (Waters et al., 1989; Buss et al., 1989; Waelkens et al., 1995). The greyness of the 'linear' component suggests rather large grains, and is consistent with the smaller-than-average colour behaviour for the optical extinction; an accurate description of this component in the near-UV is hampered by the prominence of the bump, however. The central wavelength of the circumstellar bump of HD 213985 is significantly larger than that of the interstelllar bump, and the width of the feature is about twice the typical value of the interstellar bump.

4. VARIABILITY

We obtained during the IUE mission a total of 4 low resolution swp+lwp spectra of HR 4049 and 6 pairs of HD 213985 spectra at irregular intervals. Interestingly, some components of the extinction curves towards both objects proved to be variable. Because of

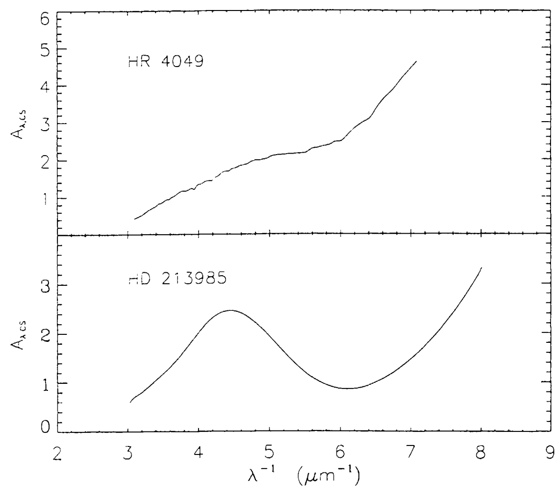

Figure 2. The UV extinction curve of the circumstellar envelopes of HR4049 and HD213985.

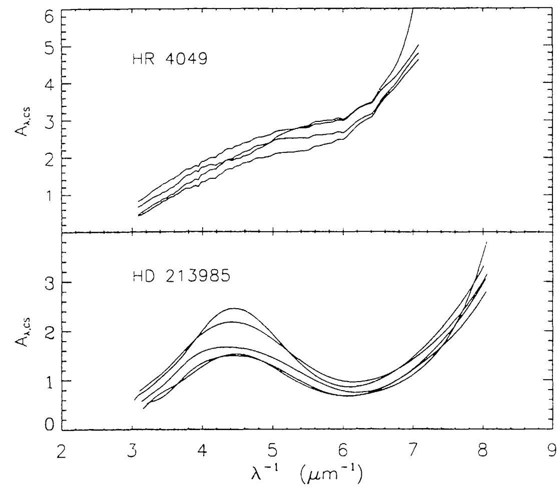

Figure 3. The variability of the UV circumstellar extinction curves of HR 4049 and HD 213985

the erratic component in the extinction a correlation with orbital phase is not sufficient to interpret the variability in full detail. It appears, however, that at least the linear component of the UV extinction correlates well with the obscuration observed in the optical.

For HR 4049 the amplitude of the variability of the linear component is within the observational uncertainty equal to the value expected from extrapolation of the amplitudes of the optical photometric passbands. Though no simultaneous UV and optical observations could be scheduled, it appears that higher UV extinction occurs at orbital phases when the optical extinction is largest. There is, moreover, some evidence that also the far-UV rise is variable: it was much higher than average on the spectra obtained on November 30, 1993 (see figure 3).

The variability measured in the extinction curve of HD 213985 is shown in fig. 3 as well. From the fact that the flat 'grey' component in the UV extinction attains at 6 μm^{-1} an amplitude which is larger that the optical extinction, it appears that the flat UV extinction component indeed represents the linear component in the extinction curve. The slope, if any, is however not well defined, and accurate near-UV fluxes should clarify this issue. The optical photometric data, although unfortunately not at the same epoch, indicate that the UV extinction indeed follows the optical extinction. The slope of this linear component indicates the grains responsible for the optical absorption to be rather large and certainly larger than in HR 4049.

In order to quantify the variability we used the parameterisation of the extinction curve as described by Fitzpatrick & Massa (1986). Because of the impossibility of determining accurately the linear part of the extinction curve, any detailed quantitative analysis of the two other components must be considered with caution. Nevertheless, it appears that the variability at the shortest wavelengths is more due to the linear extinction than to the far-UV rise, which is thus constant. The most interesting fact is that the 220 nm bump is clearly variable; there is substantial evidence that this variability is in phase with the variable linear component: the two spectra with the largest linear component also show the largest bump.

5. THE 220nm BUMP

The carriers of the interstellar 220 nm bump have still not been determined without ambiguity (Mathis 1990). The most popular candidate is graphite, which has a resonance which occurs with the right wavelength, width and strength to produce the bump, and which involves a carrier (carbon) that is abundant in the interstellar medium. However, observations of carbon stars suggest that amorphous carbon, not graphite, is injected into the interstellar medium. The production of the interstellar absorbers from amorphous carbon would then involve the destruction of larger amorphous grains by the interstellar UV radiation (Hecht 1986). Blanco et al. (1993) studied in the laboratory the dehydrogenation of amorphous carbon grains by annealing, and were successful in producing grains which showed an absorption feature not unlike the interstellar one. In order to explain the remarkable constant wavelength of the bump along all the line of sights in the ISM, a very restricted size distribution of small grains is required (Whittet, 1992).

Hecht (1986) observed a broad circumstellar bump for R Coronae Borealis; in this object the circumstellar bump is much broader than the interstellar bump, and is centered at 240 nm. The larger central wavelength is interpreted in terms of a larger grain size.

The characteristics of the UV absorption bump of HD 213985 are intermediate between those of the interstellar interstellar feature and that of R CrB: the central wavelength is about 228 nm and the width is larger than for the interstellar feature but smaller than for R CrB. We note that HD 213985 is a hotter star than R CrB. It is then natural to conclude that the annealing process is more advanced in the case of HD 213985, where the UV flux is more important than for R CrB. Another important difference may be that the initial grain composition is different, HD 213985 being less carbon rich than R CrB.

Further constraints on the possible carrier comes now from a detailed comparison of the circumstellar material around HD 213985 and HR 4049. It is puzzling that no UV bump is observed for the post-AGB binary HR 4049, since also the star is C-rich. The circumstellar dust of this source is characterized by a population of very small carbon-rich circumstellar particles, since it displays the circumstellar UIRs (see below), that are often attributed to large carbon-rich molecules (Léger and Puget 1984) and a steep far-UV rise; on the other hand, the optical photometric behaviour and linear UV extinction of HR 4049 show that also larger grains must occur. It then seems that quite some fine tuning is required to produce the right conditions for the formation of the carriers of the bump to occur.

6. ISO SPECTRA

From the discussion above it appears that the monitoring of the UV and optical extinction of HR 4049 and HD 213985 may contain clues about the carriers of the circumstellar, and, by inference, interstellar extinction, but that unambiguous conclusions are hard to draw. The objects offer, however, the exceptional opportunity to observe the circumstellar dust directly from its infrared emission. We had access to full AOT1 spectra of both sources with the Short Wavelength Spectrometer (SWS) on board the Infrared Space Observatory (ISO) (de Graauw et al. 1996; Kessler et al. 1996). Both spectra are displayed in Figure 4.

The mid-IR spectrum of HR 4049 is dominated by the full set of the well-known infrared emission bands at 3.3, 6.2, 7.7, 8.6 and 11.3 μm on top of a warm continuum (Beintema et al., 1996; Molster et al., 1996). The bands are usually attributed to C-C and C-H stretching and bending vibrational decay of an aromatic hydrocarbon molecule after excitation by a UV or visible photon. Detailed analysis of the excitation and emission process indicates that the carriers of the bands are quite small, i.e. comprising of the order of 50 atoms (see e.g. Allamandola & Tielens 1989). HR 4049 shows remarkable structure in the main bands. The relative strength of the bands and especially the high 7.7/11.2 μm band-ratio is indicative of the charge state of the collection of PAH molecules which must be for HR 4049 almost completely ionised. The absence of any plateau band emission and the strength of the 3.3 μm emission are interpreted as due to a very high proportion of small particles. The high optical-UV radiation field at the location of the circumbinary disc around HR 4049 may induce multiple photon excitation, strengthening the 3.3 μm band even more (Molster et al., 1996). One may conclude that the IR spectrum of HR 4049 indicates a high abundance of small, ionized, hydrogen-rich and highly excited PAH's.

The IR flux level of HD 213985 is unfortunately rather low for high-S/N spectroscopy with ISO, but sufficient to point out that the mid-IR bands often attributed to PAHs are weak or absent. A broad emission is observed in the range between 8 and 12 μm. The interpretation of this emission band deserves further study, however. Between 8 and 10 μm this band is reminiscent of silicate emission, while between 10 and 12 μm it more closely resembles the SiC band that is observed around carbon-rich objects. A possibility is, however, that the whole band is due to silicates, with amorphous material dominating at the shorter wavelengths, and with a crystalline component centered on 11.3 μm; in fact the feature is not unlike that observed by ISO for O-rich circumstellar shells of young stellar objects (e.g. Waelkens et al. 1996).

The IR energy distribution of HD 213985 is more complex than that of HR 4049, in the sense that for HD 213985 a cool-dust component is present in addition to the circumstellar disk close to the central binary. It cannot be excluded that this cool dust component is the result of earlier mass loss when the star was still oxygen-rich, and that the 10 μm emission originates from silicates that do not occur in the circum-binary disk. It may then be that the study of correlations of the IR emission with the UV extinction should focus on the nearer-IR part of the spectrum. In this context, it is noteworthy that Whitelock et al. (1989) monitored the near-IR variability of HD 213985 and found a behaviour that could not be explained in terms of variable circumstellar extinction alone.

7. DISCUSSION

In principle, HR 4049 and HD 213985 appear to be ideal sources to test several hypotheses concerning the carriers of the different components of the interstellar extinction law, because of the exceptional opportunity to probe the circumstellar dust both in absorption and emission, with the variability as a bonus. Nevertheless, the picture that can be drawn from the observational data available so far is not clearcut.

It appears rather likely from the results with respect to HR 4049 that a link may exist between the presence of the small particles responsible for the infrared emission bands and the far-UV extinction rise. When comparing the ISO spectra with literature results (e.g. Cohen et al. 1989), it appears a distinct possibility that the strength of the emission bands in HR 4049 is variable. It is then a subject for future research whether such a variability could correlate with variability of the circumstellar far-UV extinction of this star. It is somewhat puzzling, however, that a circumstellar far-UV rise occurs for HD 213985, while the infrared emission bands for this star are weak at most.

On the other hand, the absence of a circumstellar extinction bump for HR 4049 argues against an interpretation of the carrier of this feature in terms of

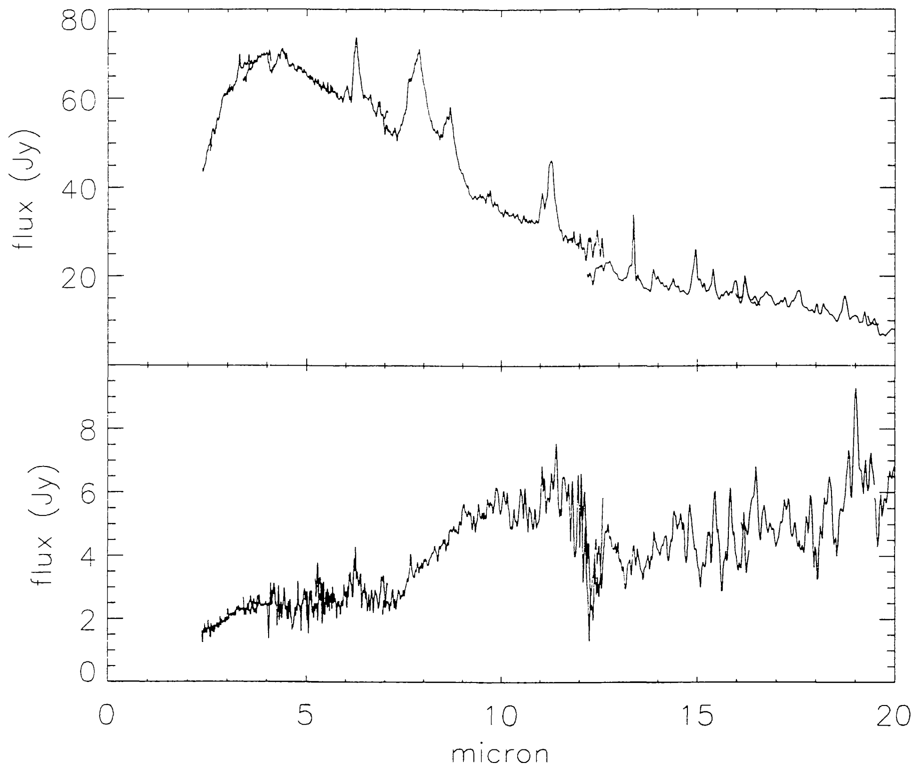

Figure 4. The SWS spectra of HR 4049 (upper panel) and HD213985 (upper panel) from 2.4 to 20 μm.

PAHs (Waters et al. 1989). The observation of circumstellar CH^+ absorption in addition to a strong circumstellar extinction bump for HD 213985 can seen as evidence for a picture in which dehydrogenation of amorphous carbon through annealing intervenes. However, no argument for such a picture could be found from the IR observations of the circumstellar dust of HD 213985.

8. CONCLUSION

The research we have summarized in this contribution highlights the importance of *multiwavelength observations* and also of *monitoring* of variable sources. In this study, as in many others, IUE has set a landmark, because of its unique possibility for flexible scheduling in a wavelength region that is crucial for many astrophysical processes. It can be regretted that IUE was not available any more once ISO was launched, so that strict simultaneity of UV and IR observations has not been possible for this project. Nevertheless, it is clear that the experience with IUE will be the guide for future observational campaigns.

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